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CANDU Fuel: Design/Manufacturing Interaction

by:

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ABSTRACT

The design of CANDU fuel has been the product of intense cooperation among fuel designers and fuel manufacturers. The developments of some of the novel processes in fuel manufacture are outlined. These include the brazed-split-spacer design, the resistance welded endcap and CANLUB coatings.

INTRODUCTION

The evolution of many features of CANDU fuels has been the product of intense interaction and co-operation between the fuel designers and fuel manufacturers. The fuel engineers established the general design requirements for the fuel and fuel manufacturers developed the processes and equipment to manufacture the fuel, at a production scale.

In the early stages of the design of a new reactor, the fuel design requirements would be established. The general procedure was then for the fuel design engineers at AECL to request the fuel manufacturers to provide prototype fuel elements or bundles for irradiation testing in the NRX or NRU reactor test loops at Chalk River Labs (CRL). This request took place in several stages; it often started with contracts for process development, where new features were contemplated, and then continued with contracts for small quantities of fuel elements and fuel bundles for the irradiation testing program. The manufacturing processes have evolved from these early "first-off" model shop scale methods to well established controlled production processes today.

Throughout the development of fuel designs and manufacturing production methods, the emphasis has always been on product quality, manufacturability and fitness for purpose; i.e. defect free fuel for the burnup life of the fuel under normal operating conditions, including fuel handling.

BRAZED SPLIT SPACER DESIGN

In my opinion, the brazed-split-spacer concept is one of the more significant developments in the evolution of the CANDU fuel design. It was first incorporated in the 19-element Douglas Point fuel bundle[1] and has become the mainstay in all later CANDU fuel designs. (Figure 1,2) The evolution to this design concept did not come easily and went through many trials and tribulations, mainly during the late fifties and early sixties.

The earlier fuel design for NPD, and initially for Douglas Point, employing the welded-wire-wrap concept for inter-element spacers and bearing pads, had performed well. However, out-reactor testing at higher flow rates that would be required in later reactor designs, had shown evidence of fretting damage of the thin wall fuel sheath by the contacting wire spacer. The concern for this fretting damage prompted a search for other design approaches that would avoid this problem. This split-spacer approach was identified fairly early-on; however, finding a good method of attachment of the split-spacer to the sheath was more elusive. The methods that were considered included various forms of resistance welding and resistance brazing; but they all had serious drawbacks[1,2]. Resistance welding had concerns for possible crevice corrosion in the gap under the pad and for possible damage to the fuel sheath by the welding process. Resistance brazing showed some early promise but the process became nearly impossible, due to current shunting when trying to assemble more than two or three elements at a time.

During the 50's, researchers at Armour Research Labs had been looking for possible brazing alloys for zirconium[3,4]. From all the alloy systems that were investigated, which included aluminum, copper, iron, nickel and others, they concluded that the Zr-5 w/o Be eutectic (m.p. 960°C) could be recommended (Figure 3,4); it had good joint wetting properties and high mechanical strength and exhibited reasonable corrosion resistance in high temperature water.

In 1958 we, in Canada, began a program to develop methods to braze spacer appendages on fuel sheaths[5]. Initially, the thrust was to obtain quantities of the brazing alloy and to examine ways of applying these in the spacer/sheath joint. Small ingots of the Zr- 5 w/o Be alloy were obtained from reactive metal suppliers: Mallory, Heraeus, Nuclear Metals Inc. (NMI), and Nuclear Material and Equipment Co. (Numec). This alloy is very hard and attempts to form it into useful shapes for prepalcement were not successful, although NMI did produce a small quantity in wire form. Other developments included preplacing the alloy in the joint as a powder paste, like Nicrobraz for stainless steels. Although samples of powder were made, by pre-hydriding, crushing/grinding and de-hydriding, its use as a brazing alloy was not successful; the powder was difficult and messy to preplace on the parts and the brazed joint was very poor due to much porosity.

A break-through in the problem of preplacing the brazing alloy came with the discovery that beryllium metal would react directly with Zircaloy to form the Zr-Be brazing alloy in-situ. This led to preplacing the beryllium as a vapour deposited coating on the spacer component. The development of methods for vapour coating beryllium was further assisted by being able to use a small bell-jar coating unit in a beryllium handling facility that was already established at Westinghouse labs in Hamilton. This facility provided beryllium coated Zircaloy sheet samples which were then used to form spacer and bearing pad appendages for the development of brazing methods[6].

A further breathrough in spacer brazing was the development of vacuum induction brazing for heating the joint to the eutectic melting temperature[6]. This led to the development of a unit which was able to braze many sheaths at one time. (Figure 5)

RESISTANCE WELDED ENDCAPS

A very early example of design/manufacturing interaction is the resistance welded endcap for sealing the ends of fuel elements[7]. The very early CANDU fuel for the NPD reactor had fusion welded endcaps, but fuel manufacturers recognized that the fusion welding process would become very onerous in practice, recognizing the large numbers of fuel element end closures required in the short fuel bundle in CANDU reactors. In looking for alternative end closure processes, the fuel manufacturers were attracted to resistance welding methods; this is an inherently fast process, well suited to repetitive production requirements, and the resistance welding technology and control equipment had been developed to a high degree for the aircraft industry. As early as 1958 the fuel manufacturers had assembled developmental equipment and were providing resistance welded endcaps on experimental fuel elements for irradiation testing in test loops at CRL.

The endcap weld is essentially a ring projection weld between the outer rim of the endcap and the end of the fuel sheath; it would be equivalent to a line resistance weld about one and a half inches long. All CANDU Fuel manufacturers employ similar endcap welding processes but there are detail differences; the internal endcap geometry, and the shapes of the flaying surfaces to be welded, are proprietary to the fuel manufacturers. The external shape of the endcap is specified by the fuel designers and is required to accommodate the fuel handling tooling, i.e. side-stops and latches.

A section through the endcap weld from one manufacturer is shown in Figure 6. To make the weld, the endcap is held on the end of one electrode and the fuel sheath is held in essentially a ring collet which is the other electrode. An axial force is applied at the same time as the resistance welding current is discharged, heating the interface and forming the weld. The weld is really a hot forging process and the excess material from the weld upset, termed the weld flash, pushes out at both sides of the weld. In a subsequent operation, the external weld flash is machined-off to maintain the specified diameter of the fuel element.

Today's endcap welding process is essentially the same as that developed more than thirty years ago, although the quantity of fuel manufactured each year has increased many fold. The manufacturers have accommodated these increased quantities while maintaining high quality levels, through improved tooling, programmable process controllers and automation for material and product handling.

CANLUB COATINGS

Another significant development in the evolution of CANDU fuel designs has been CANLUB coatings. This development was driven by the urgency to provide a fix to prevent fuel failures following power changes during on-power refueling. Although this problem had occurred at Douglas Point it became more serious during the early operations of the Pickering reactors during the early seventies. Comparison of the crack morphology in fuel sheaths from power ramped fuel bundles, with cracking produced in the laboratory in iodine mixtures, had suggested that the defects were due to a stress-corrosion-cracking (SCC) mechanism. It was believed that iodine, or other SCC corrodents, originate in the fission products which are released from the fuel into the fuel-sheath gap.

An industry-wide working party was set-up to investigate the power-ramp defect problem and to find a solution. Most of the remedies that were suggested were aimed at reducing the pellet/sheath friction during fuel expansion; these included graphite coatings on the sheath interior or on the pellet surface, low density pellets and pressurized elements. From tests of these, graphite coatings proved to be most consistently effective. The first graphite coatings employed were on fuel elements which were tested in NRX reactor loops[8]. These coatings employed DAG 154, a graphite filled lacquer which was available at CRL and is supplied commercially by Acheson Colloids Ltd., primarily to the electrical industry for use as conductive coatings. The CANLUB graphite coatings were so successful in preventing power ramp defects that fuel manufacturers were requested to set up production facilities as soon as possible.

The initial CANLUB coating procedure employed at CRL involved smear-coating the DAG - 154 lacquer on the inside surface of the fuel sheath, followed by air drying to evaporate the solvents and baking in a vacuum oven at about 350 °C to decompose and drive-off the organic binder (Figure 7). The manufacturers proceeded to set-up essentially similar processes for applying CANLUB coatings on a production basis. Very quickly the manufacturers began producing CANLUB coatings in limited quantities, employing bench-scale fill-and-drain or flood coating-and-drain techniques followed by vacuum baking in laboratory vacuum furnaces.

In order to employ CANLUB coatings in as many Pickering fuel bundles as possible, from these limited early facilities, the fuel designers initially specified CANLUB in only the outer elements. This allowed CANLUB fuel bundles to be employed quickly in the more vulnerable high power channels. This requirement for CANLUB in the outer elements only has persisted in Pickering fuel until fairly recently when the inconsistency was recognized; Pickering fuel is now supplied with CANLUB coatings on all fuel elements.

In a fairly short time manufactures were able to increase CANLUB coating capacities, once production scale coating and baking facilities were procured and installed. Overtime the CANLUB coating process at the manufacturers has remained almost unchanged, although production capacities and productivity have increased considerably with process automation and various degrees of robotization for material handling.

References:

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6) K. T. Bates, "Brazing of Zircaloy in Nuclear Fuel", Proceedings Nucl. 66 (1966), also AECL-2813 (1966)

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Figures

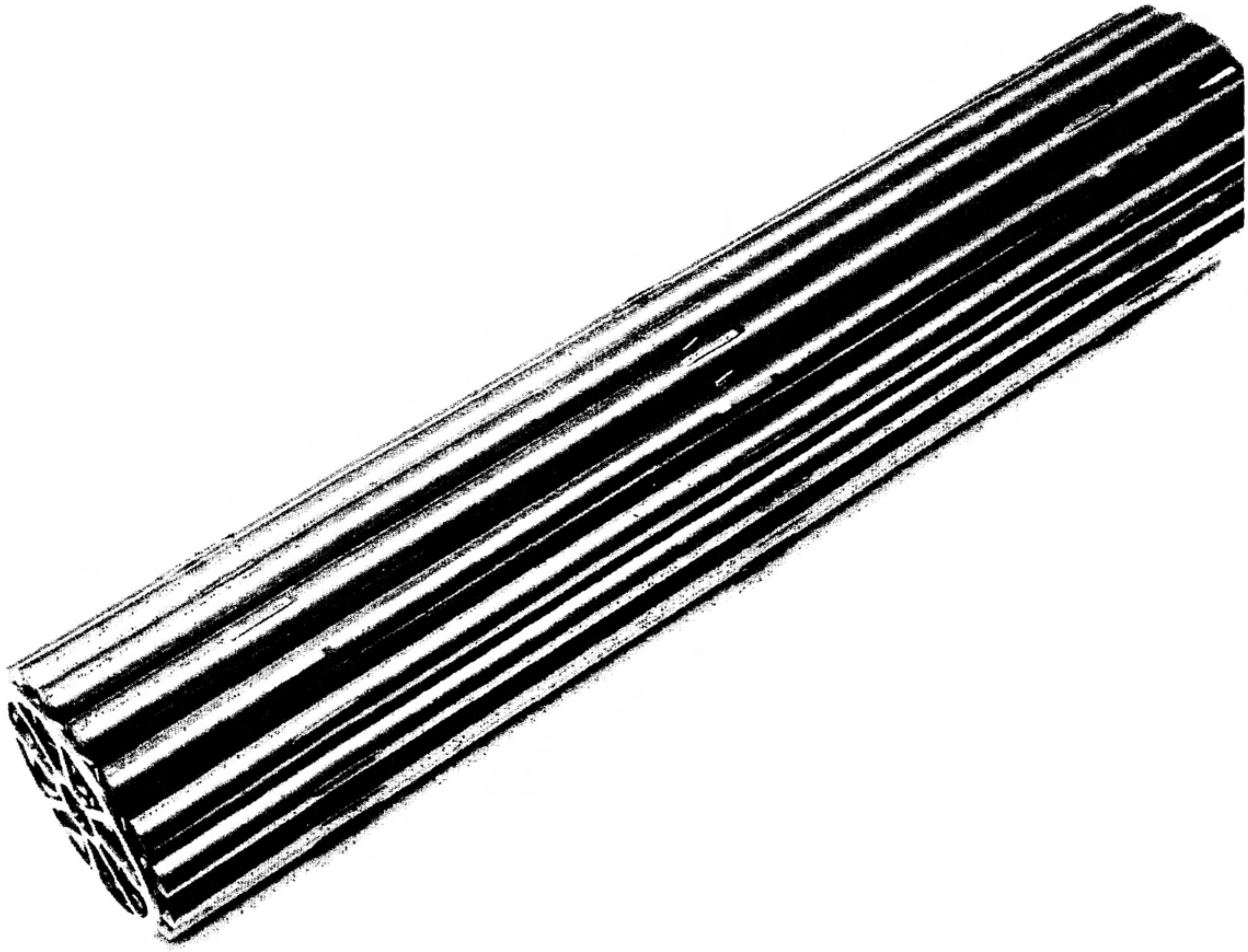

Figure 1 Pickering 28 Element Fuel Bundle; Brazed-Split-Spacer Design

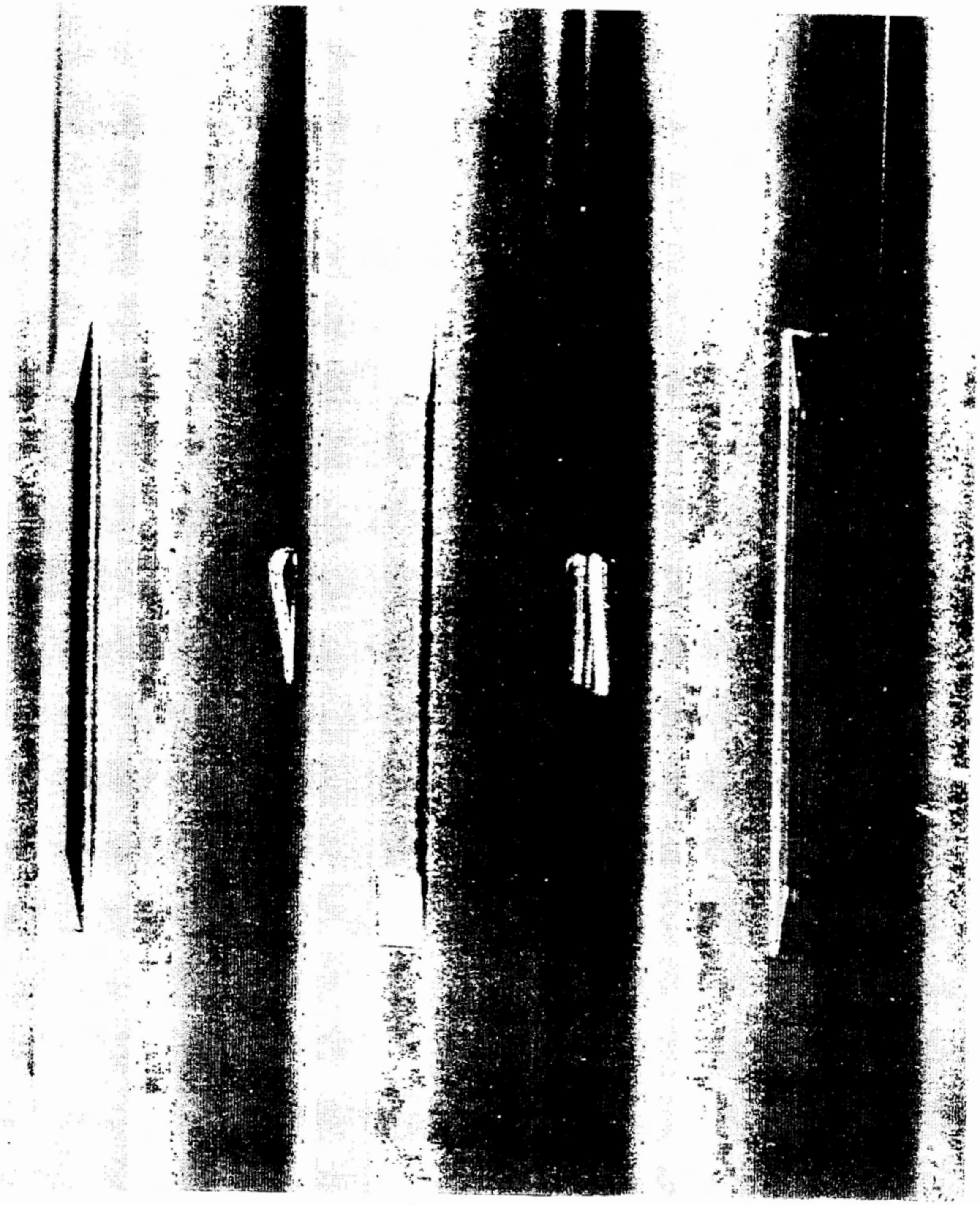

Figure 2 Close-up of Brazed-Split-Spacers and Bearing Pads

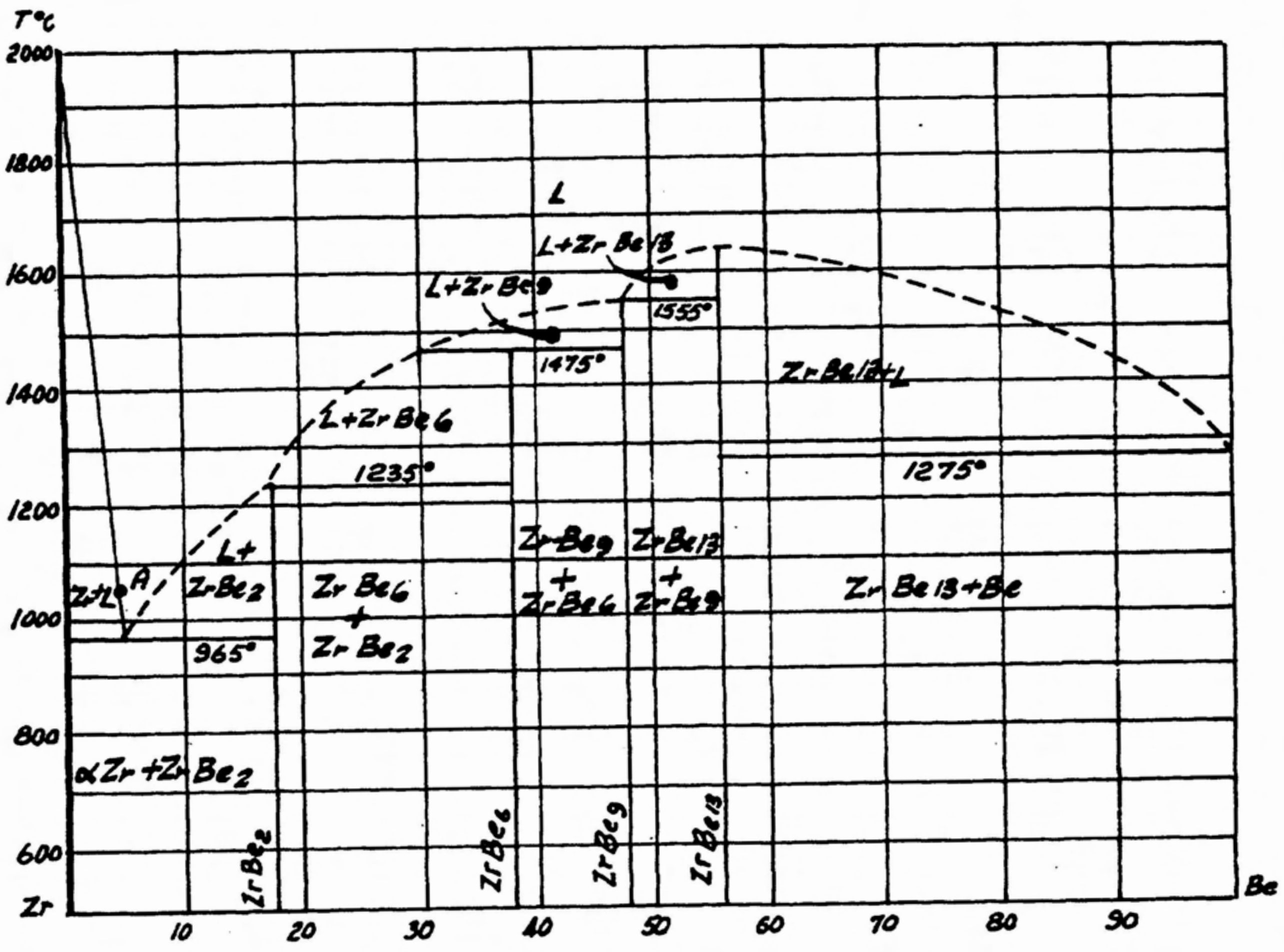

Figure 3 Phase Diagram Zr-Be System

Figure 4 Metallographic Section of Brazed Fillet Joint

Figure 5 Early multiple-tube vacuum induction brazing

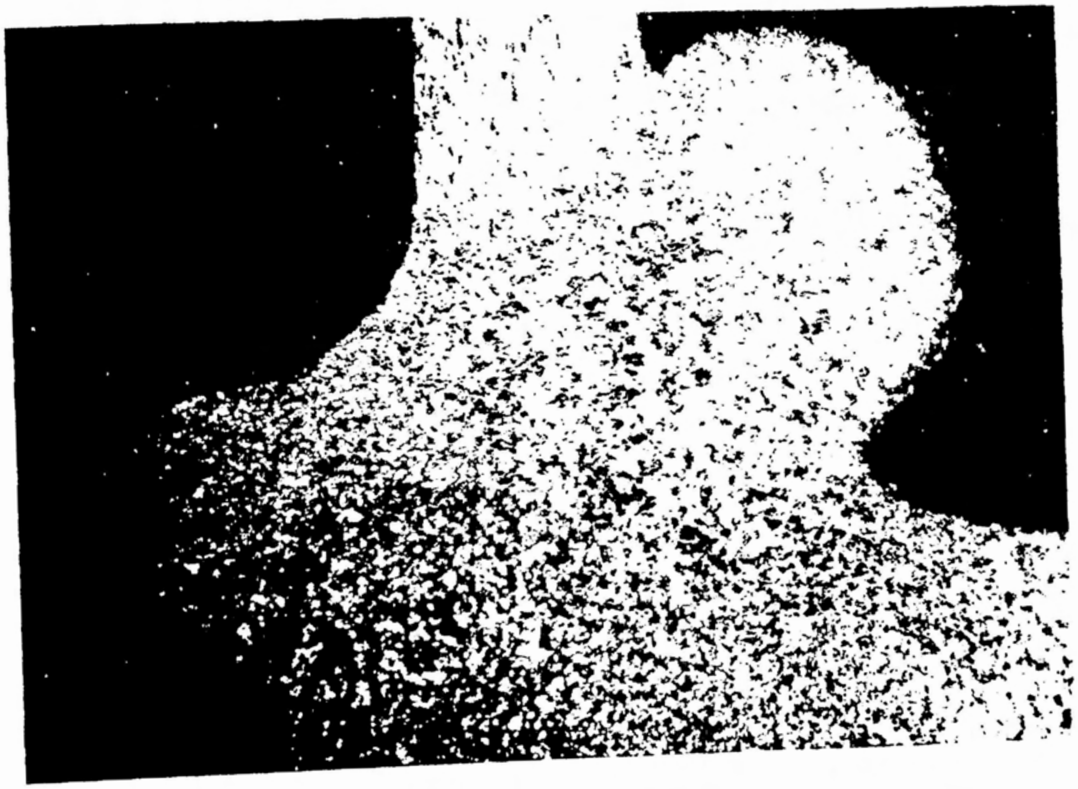

Figure 6 Section through end cap resistance weld

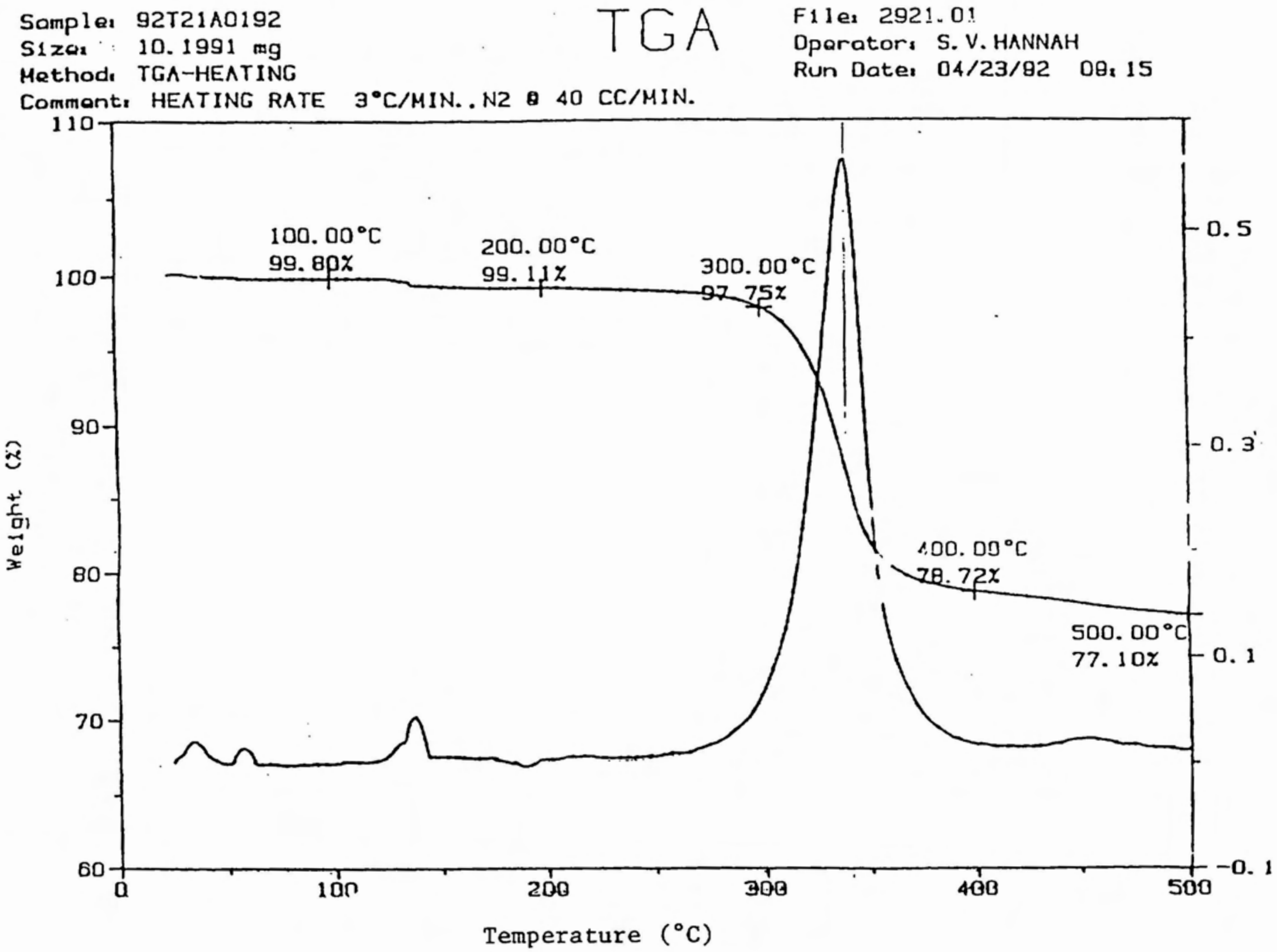

Figure 7 Thermogram Alcadag 154